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Abstract. Ap/Bp stars are magnetic chemically peculiar early A and late B type stars of the main sequence. They exhibit peculiar surface abundance anomalies that are thought to be the result of gravitational settling and radiative levitation. The physics of diffusion in these stars are reviewed briefly and some model predictions are discussed. While models reproduce some observations reasonably well, more work is needed before the behavior of diffusing elements in a complex magnetic field is fully understood.

1. Introduction

Ap/Bp stars are chemically peculiar stars in which in which relatively strong magnetic fields have been measured (see Ryabchikova 1991; see also the many other papers devoted to these stars in these proceedings). They are early A and late B stars, ranging from 8000 to 15000 K in effective temperature, in which large abundance anomalies have been found. Their magnetic fields typically of the order of 1 to 10 kG.

Ap/Bp stars, while similar in many ways to other main sequence chemically peculiar stars, have quite specific abundance anomalies. They are typically enriched in rare earth elements and some lighter elements such as silicon. They have been found to feature surface composition inhomogeneities (e.g. Kushnig et al. 1999, see also Hatzes 1996) and to have a stratified atmospheric composition (e.g. Ryabchikova et al. 2002). As the main difference between them is the presence of magnetism in Ap stars, the understanding of the formation and evolution of the chemical composition in Ap stars may yield a new understanding of the structure of the magnetic fields.

Some of the cooler Ap stars are pulsating, the so-called roAp stars. Those stars are within the boundaries of the classical instability strip where pulsations are driven by the opacity of helium. As diffusion leads to helium deficiencies, it is a challenge to ensure that the required opacity is maintained in the driving region for the κ-mechanism to be efficient. Therefore, the modeling of the stratification in Ap stars is of central importance to the study of roAp stars.

2. Diffusion in Stars

Diffusion is defined here as the relative drift of elements with respects to each other. This drift occurs when forces acting on the the components of the stellar plasma differ from species to species. The term settling refers to the inward drift of heavier species with respect to light species under the action gravity only. In this section I will briefly describe the main physical processes that lead to (or inhibit) diffusion in stars, starting first with a general description, followed by a more specific discussion of diffusion in the presence of magnetic fields.

The types of stars in which diffusion occurs depend on how fast diffusion can affect the abundances and what are the competing processes. Stars with appreciable surface chemical peculiarities are slowly rotating stars that feature low mass loss and shallow surface convection zones, i.e. early F to late B main sequence stars (Michaud et al. 1976), white dwarfs (Fontaine & Michaud 1979), and hot horizontal branch stars (Michaud, Vauclair, & Vauclair 1983). Long lived low mass stars can be significantly affected by diffusion in the core (Proffitt & Michaud 1991).

2.1. Diffusion in Non-magnetic Stars

In non-magnetic and slowly rotating stars, spherical symmetry can be assumed. Diffusion will lead to vertical (radial) stratification of the elements but not to inhomogeneities on the surface. Diffusion in non-magnetic stars has been studied extensively in the past (see Michaud et al. 1976; Richer, Michaud, & Turcotte 2000; and references therein) and so will be described here only very briefly.

The variation of composition for an element i with time can be calculated from the continuity equation

$$\frac{\partial c_i}{\partial t} = -\frac{\partial}{\partial r}\left(c_i v_D(i)\right) ,\tag{1}$$

where the diffusion velocity is expressed as (Babel & Michaud 1991a)

$$v_D(i) = D_i\left\{-\frac{\partial c_i}{\partial r} + \frac{A_i m_p}{kT}(g_{\mathrm{rad;i}} - g) + \alpha\frac{\partial \ln T}{\partial r} + ...\right\},\tag{2}$$

or a similar expression. The diffusion coefficient D_i is mainly determined by collisional cross sections and, as the Coulombian interactions dominate, on the degree of ionization of species i. It is an average of the diffusion coefficients of the individual ionization states of species i. The term including the temperature gradient is the thermal diffusion term. Its coefficient α is also determined by collisional cross-sections. One may add a turbulent diffusion coefficient to D_i to account for turbulent particle transport, such as due to convection.

The most important factors that determine the amplitude and sign of $v_D(i)$ is the net effect of the inward gravitational acceleration and the outward radiation acceleration, $g_{\mathrm{rad;i}} - g$. If $g - g_{\mathrm{rad;i}} \geq 0$, then the species will levitate, whereas it will sink if $g - g_{\mathrm{rad;i}} \leq 0$. The radiative acceleration g_{rad} is highly dependent on the ionization state and the atomic properties of the species. In the absence of mass loss, the stratification and the photospheric abundances are determined in the most part by the combined effects of gravity, radiation pressure and convection (or mixing).

The radiation acceleration on a species decreases when its abundances increases because of saturation. It also depends to a lesser degree on the abundance of other elements because of the competition for photons in overlapping lines for example (Michaud et al. 1976; Richer et al. 1998).

Where the diffusion time scales are short, the abundances will reach an equilibrium (i.e. a null total velocity). It is an appropriate assumption in the atmosphere of Ap stars when evolutionary effects are neglected, i.e. the static case. In the simplest possible case, where only gravity and radiation pressure are taken into account, the equilibrium will be reached when the composition has evolved so that the radiative acceleration balances gravity. The equilibrium solution is in fact more complicated due to the contributions of other processes, including mass loss.

There are other microscopic processes that may have to be considered in the relatively cool and outer regions of stars if they are stable. One is ambipolar diffusion through which protons and electrons drift with respect to hydrogen atoms which would in turn affect the drift of other species (Babel & Michaud 1991c). Another that has so far not been shown to be significant in Ap stars is light induced drift which can arise from an anisotropic radiation field in spectral lines (LeBlanc & Michaud 1993).

2.2.   The Effect of Magnetic Fields

Magnetic fields have several consequences, direct and indirect, on how diffusion will affect the chemical composition.

Effect on drift of ionized species. The magnetic field reduces the diffusion coefficients in the direction perpendicular to the magnetic field lines (Michaud, Mégessier, & Charland 1981). This effect is proportional to the strength of the field and to the charge of the species. Neutrals do not feel the field while ions do. As a result, the drift of ionized species across field lines may be impeded and they might have a tendency to drift along the field lines.

Effect on radiative accelerations. Radiative accelerations are mostly due to absorption in spectral lines. In the presence of a magnetic field the degeneracy of the lines may be lifted. In lines that are saturated, this will reduce the saturation and increase the radiative acceleration by factors up to 50 (Borsenberger, Michaud, & Praderie 1981; Alecian & Stift 2002). A smaller effect is that an horizontal component to radiative acceleration is induced which can potentially have significant effects on some species (Babel & Michaud 1991b).

Effect on convection. Convection can be suppressed in the presence of strong vertical field lines. Balmforth et al. (2001) have shown that convection would be expected to be strongly suppressed at the magnetic poles for stars with a field as small as 10^3 G. At the magnetic equator however, they argue that the magnetic restoring force is not able to compete against buoyancy and that convection is not suppressed, although the field might maintain some coherence in fluid motions. Turbulent motions that occur above the convection zone in non magnetic stars may be stabilized in in the presence of the magnetic field.

The combined effects of introducing magnetic fields in diffusion calculations is that it breaks the spherical symmetry leading to surface variations of abundances. This creates a map of the surface magnetic field that can be decoded with a proper modeling of horizontal abundance inhomogeneities with respect

to the geometry of the magnetic field. It will also lead to a different vertical stratification than in the non-magnetic case because of the changes in mixing and radiative accelerations.

3.   Application to Ap/Bp Stars

In this section we will review some results and expectations for Ap/Bp stars.

The goal is, naturally, for models of Ap/Bp stars to be able to reproduce surface inhomogeneities comparable to observations, in amplitude and in morphology, as well as predicting the correct vertical stratification. Because of the complexity of the problem, most models have included many simplifications, e.g. treating the magnetic poles and equator, where the field lines are either vertical or horizontal, separately, or assuming a very simple magnetic geometry, However simplified, these models provide predictions as to which elements should be over- or under-abundant depending on specific field geometries that can be compared to observations.

3.1.   Magnetic Poles - Vertical Field Lines

As mentioned above, the convective structure at the poles and equator is different. Convection is expected to be suppressed, or at the very least substantially reduced, at the poles. On the other hand, the vertical field lines do not impede mass loss whereas the horizontal field lines at the equator trap the wind but allow convection to occur. At the poles, diffusion in Ap stars is comparable to diffusion in hot non-magnetic stars, such as the HgMn stars. The vertical stratification will mainly determined by the competition between diffusion and mass loss with no impact from the field lines as they are parallel to the motions. Radiative forces are affected by the magnetic field as discussed above.

Babel & Michaud (1991a) produced a parameter free model for the star 53 Cam that showed that simple diffusion is not sufficient to reproduce the observed surface abundance inhomogeneities and that another physical process, most probably mass loss, is needed. They estimated that a mass loss of the order of 10^{-12}-10^{-14} $M\odot\,yr^{-1}$ is required. Mass loss of that order would be typical of A stars in general, magnetic or not. Babel (1993) added mass loss to the model and claims to reproduce the observations qualitatively. Vauclair, Dolez, & Gough (1991) examined the behavior of helium at the poles of an Ap star to see if enough helium could be maintained in superficial regions to account for the pulsations of roAp stars (helium has a very small g_{rad} at normal abundances and therefore always settles). They show that a helium reservoir can indeed be maintained with a mass loss of the order of 10^{-13} $M\odot\,yr^{-1}$.

The composition of He depends only on the strength of the mass loss, but for other elements a lot will depend on the profile of the radiative acceleration for each species. Some species may be preferentially lost in the wind while others will accumulate in the line forming regions. Species that aren't radiatively supported in the upper atmosphere will not be dragged by a metallic wind in which H and He are not expelled (Babel 1994).

In such models the mass loss rate is essentially a free parameter since the values needed to affect diffusion are below the threshold of detectability. However, Ap stars offer the opportunity of constraining the mass loss by comparing

predicted and observed polar abundances, provided the radiative accelerations are known with sufficient accuracy.

Recently, an effort has been initiated (Michaud et al. 2002) where consistent diffusion of multiple species as has been done in non-magnetic stars for several years (Richer et al. 2000, and references therein). Their *calculations do not take* the effects of magnetism on diffusion apart from a reduction in mixing relative to Am stars.

3.2. Magnetic Equator - Horizontal Field Lines

Wherever the field lines are nearly horizontal, convection is thought to occur but mass loss is not. The magnetic field should stabilize the atmosphere and allow stratification to form above the convection zone. Ions and neutrals will behave differently as the vertical motions cross field lines.

The magnetic fields in Ap stars are low enough so that their effect on diffusion is expected to be limited to the most superficial regions of the stars. Horizontal fields stronger than 10^5 G would be needed to prevent species from being pushed upward in the line forming region (Michaud et al. 1981).

As a result, elements that are not radiatively supported, such as He or O, will be depleted from the equatorial regions. Elements that are pushed outward by the radiative forces will likely be trapped by the field lines and will accumulate and be observed as being overabundant.

In the cases where there is a large fraction of neutrals and where the neutral and ions do not behave similarly, i.e. the neutral being supported and ions not and vice versa, the net effect can be more complicated. For elements where the neutral is radiatively supported but the first ionized state is not, the case of Si is discussed by Michaud et al. (1981), the neutral population would be pushed upward across the field lines but the ionized population would settle. When it does so its vertical drift will be impeded by the field lines. It would tend to diffuse horizontally, and form a band around the region where the field lines are horizontal. This effect would only be seen if the reservoir for that element is limited, meaning that the element would be radiatively supported only in the upper fraction of the envelope.

The detailed distribution of elements in equatorial or intermediate regions (i.e. where the field is horizontal or oblique) will depend heavily on the details of horizontal diffusion, which remains uncertain.

4. Conclusion

Theoretical predictions for the vertical and horizontal stratification in Ap/Bp stars are now starting to become more precise. However much still lies ahead before the predictions can be considered reliable. Some recent observations of abundance patterns in Ap stars can't be easily reconciled with current theoretical expectations (e.g. Strasser, Landstreet, & Mathys 2001 for HD 187474). They present evidence of polar overabundances of some elements (Si, Cr, Mn), elements that are expected to supported by radiative pressure and therefore should be lost to the wind. On the other hand they find other abundances that are in good agreement with theoretical expectations, e.g. oxygen depletion,

enrichment in rare earth elements. As they point out, the absence of detailed models prevents meaningful comparisons with their observations.

Alecian & Stift (2002) show that one must be wary of any theoretical predictions based on incomplete models. Nonetheless, as more physics is incorporated in the models, and improved atomic data lead to more accurate diffusion coefficients and radiative accelerations, comparing the models to the observations will help us understand how convection and mixing is affected by magnetism and how mass loss takes place in A stars.

A major modeling effort needs to be done to couple the observations to the underlying physical processes. taking into account the 3-D transport processes and radiative transfer requires a large code development effort which is however possible given today's computing power.

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Discussion

Ryabchikova: Do you expect different abundance profiles for example, for Fe-peak elements, in Ap and Am star of the same effective temperature?

Turcotte: Abundance profiles are expected to differ in Ap and Am stars of the same temperature mainly because the atmospheres of Am stars is thought to be mixed, as the hydrogen convection zones in Am stars are not suppressed by magnetic fields. In Ap stars, where the atmosphere is not mixed, stratification occurs. In the interior, one should expect that diffusion in Ap stars will occur as in Am stars because the magnetic field is expected to be too small to have a significant effect.

Cally: In magnetic stars with complex magnetic structure in the atmosphere, we might expect a hierarchy of different closed magnetic loop structures. Might this lead to horizontal chemical inhomogeneities at the footprints, since we might expect more settling in high loops compared to that in low loops?

Turcotte: Wherever such loops exist we would expect the inhomogeneities to reflect the structure of the magnetic field, whatever the geometry. One would need much better modeling than available to make specific predictions.